Ground-Water Flow through Inadequately Plugged Coal Exploration Bore Holes

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by

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ABSTRACT

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Coal Exploration Boreholes

Water-level changes occurring in aquifers below coal strip mines are largely due to incompletely plugged boreholes. Thousands of boreholes were drilled during pre-mining exploration activities. Leakage through a single borehole may be in excess of one-half gallon per minute, indicating that combined leakage through all boreholes at a typical mine site could be substantial. The vertical leakage of groundwater is due to an apparent increase in vertical hydraulic conductivity in the shales that separate the aquifers. An increase of about 50 times the pre-impact value is indicated. If spoils water moves through these boreholes after reclamation, an increase in the mineral content of the deeper aquifers will occur.

Shallow aquifers are highly significant sources of water in southeastern Montana. Near coal strip mines, these aquifers are disturbed during the mining process. In the permitting process, water levels have been predicted to be lowered and water quality impacted. However, impacts to aquifers that are stratigraphically below the mine have not been predicted. Water-level declines in unmined aquifers have now been found to exceed those in the mined coal in some areas, probably due to a combination of interception of recharge by the mine and leakage to deep aquifers through boreholes.

Groundwater leakage through inadequately plugged coal exploration boreholes

I. INTRODUCTION

A. Purpose of Study

Groundwater levels have been noted to change in aquifers that underlie coal strip mines in southeastern Montana. Drawdown and mixing of groundwater appears to be occurring through inadequately plugged boreholes. The purpose of this study was to document these unexpected changes in water levels. Methods to predict future mine impacts are discussed herein.

Many holes are drilled by mining companies as part of their exploration programs for resource inventory and development. Rules that govern mining activities require that holes be plugged using specific methods. In the 1970's and early 1980's companies typically used low-solids-content-bentonite slurries, probably following the regulatory guidelines closely. However, recent work indicates the plugging methods required by law may not have been appropriate; flocculation and settling may have occurred in some holes. Mine-permit maps indicate that as many as 5,000 holes were drilled in ten square miles of the study area to represent a potentially serious hydrogeologic condition if hole-plugging is ineffective.

Groundwater and coal are important natural resources in eastern Montana. Eastern Montana coal seams are laterally continuous and highly fractured; as a result, coal beds form extensive and widely used aquifers. Both of these resources are exploited at depths typically less than 200 ft; consequently, coal extraction commonly removes large volumes of important aquifers.

Researchers and company scientists have worked to build methods to predict and explain mining impacts to hydrogeologic systems. Early predictions were based on hydrologic theory with little actual mine-impact data to validate theoretical models. In hindsight, most impacts were successfully predicted based on an understanding of the hydrogeologic systems and the mining methods. All predicted impacts were restricted to horizons above the base of coal mining. Impacts in deeper unmined aquifers were predicted to be insignificant, a presumption now apparently incorrect.

B. Study Area and Regional Geology

The study focuses on one active mining area near Colstrip in southeastern Montana. The area is in the semi-arid northern Great Plains of the Tertiary Fort Union coal region. In addition to coal, lithologies exposed at the surface are sandstones and shales

of the Tongue River Member. Alluvial gravels are present in the valley bottoms, and clinker caps the ridges. Topographic relief is produced by erosion of relatively broad valleys in non-resistant shales between ridges capped by erosionally resistant clinker.

II. OVERVIEW OF LOCAL MINING

A. Exploration and Permitting Process

Many steps are involved in opening and operating a coal strip mine. Typically, a general area of interest is established based on existing geologic maps and mineral resource reports by government agencies. Areas with potential coal reserves are compared to demographic features such as workforce availability, railroads, and other means of transportation. Once a company determines an area of interest, it applies for an exploration permit from Montana Department of Environmental Quality (DEQ).

The area of interest is explored by drilling and coring the coal seams to determine thickness, quality, and other geochemical and physical parameters. The holes are typically drilled through the target coal, with enough deeper holes to verify other resources such as deeper coal or groundwater. The number of exploration holes varies from a few widely spaced holes per square mile to hundreds per square mile with spacings of only a few hundred feet between holes. Each hole is permitted through the regulatory agency. Once the drilling is completed, the hole may be completed as a groundwater monitor well, or as is the case with the vast majority, plugged and abandoned. In the study area, exploration holes were drilled on high-density spacings to thoroughly define coal and overburden near the outcrop, and on low density spacing in areas of high overburden thickness (Figure 1).

Plugging procedures are currently specified by state and federal regulations. New plugging techniques were developed as the understanding of the effectiveness of plugging materials and procedures changed. During the first phase of major coal exploration in the 1960's, boreholes were frequently left open, except for a surface plug. Later, as new rules were written, drill cuttings were allowed and used for plugging. In the 1980's the permanent regulations regarding strip mining and reclamation were initiated and required specific abandonment materials such as bentonite slurries with specific weights of greater than 8.6 lbs/gal. However, even this requirement represents only about 10% solids by volume. In other words, settling of the bentonite can leave only the bottom 10% of a borehole plugged. Better understanding of more effective plugging materials, and better techniques are constantly being developed and implemented (Wheaton, and others, 1994). However, new technology does not affect the thousands of existing exploration holes that were plugged under old rules.

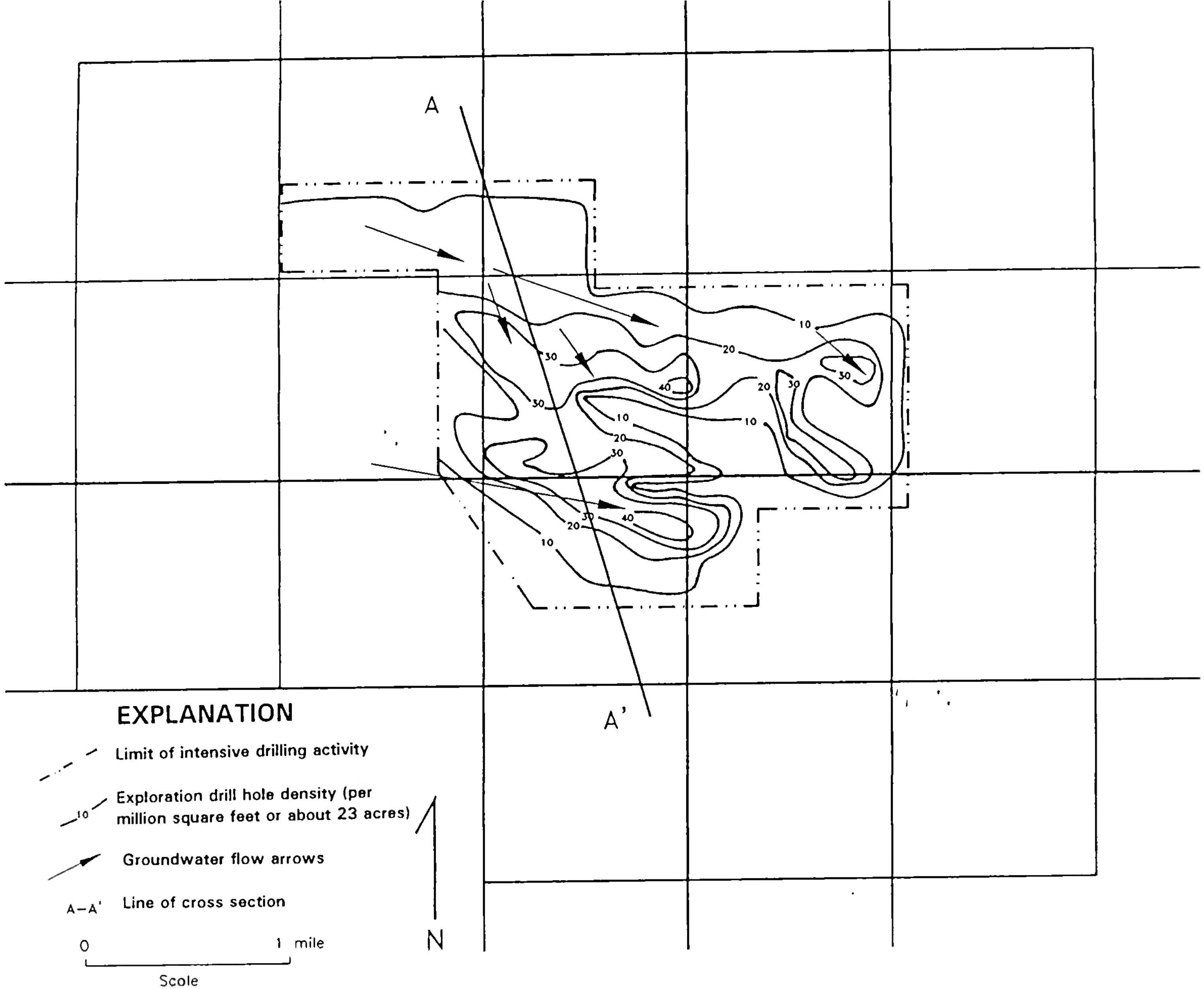

Figure 1. Contours of exploration drill-hole density in the study area, based on company data.

B. Mining Activities

At an active mine, groundwater drains from overburden and coal aquifers into the mine pit and is then pumped out to keep the work area dry. Potentiometric surfaces for all aquifers above the base of the coal develop cones of depression that terminate at the pit floor. The water that is pumped from the pit is used in mining or is discharged to a settling pond where it evaporates, infiltrates into the groundwater system, or flows to the local surface-water system.

III. HYDROGEOLOGIC SETTING

A. Stratigraphy

The shallow stratigraphy of the study area consists of shale, sandstone, and coal (Figure 2). The cross section (Figure 2), in general, is oriented across mine pits and is roughly parallel to groundwater flow direction. The sub-bituminous Rosebud coal is the target of mining in this area. The spacing and density of exploration boreholes along the cross section are shown along the bottom of Figure 2.

The overburden is generally sandstone, the interburden is mainly shale, and the underburden is shale with a fairly thick, sandstone unit just below the McKay Coal. Most of the sandstone in this area is very fine grained. Some sandstone, such as the unit below the McKay coal, is fine to medium grained.

Along streams, the alluvium contains basal clinker gravels, fine sand, silt, and clay. Clinker, formed by the burning of coal along outcrops, caps the high ridges in the area.

B. Local Aquifers

Shales in the Tongue River Member are aquitards, which transmit water extremely slowly. Hydraulic conductivity values from the shales are probably between 10^{-2} to 10^{-5} ft/day (Freeze and Cherry, 1979). Sandstone and coal are the aquifers in the area and have higher hydraulic conductivities, averaging about one ft/day (Van Voast and Reiten, 1988).

Much of the groundwater recharge originates in topographically high areas to the northwest, locally along clinker capped ridges, and in areas where aquifers outcrop. Recharge water moves generally southeast within the aquifers, and seeps vertically through aquitards to the next deeper aquifer. As shown by the equipotential lines on Figure 2, below the water table the flow is continuous, with near-horizontal flow in sandstone and coal aquifers, and nearly vertical flow through shale aquitards.

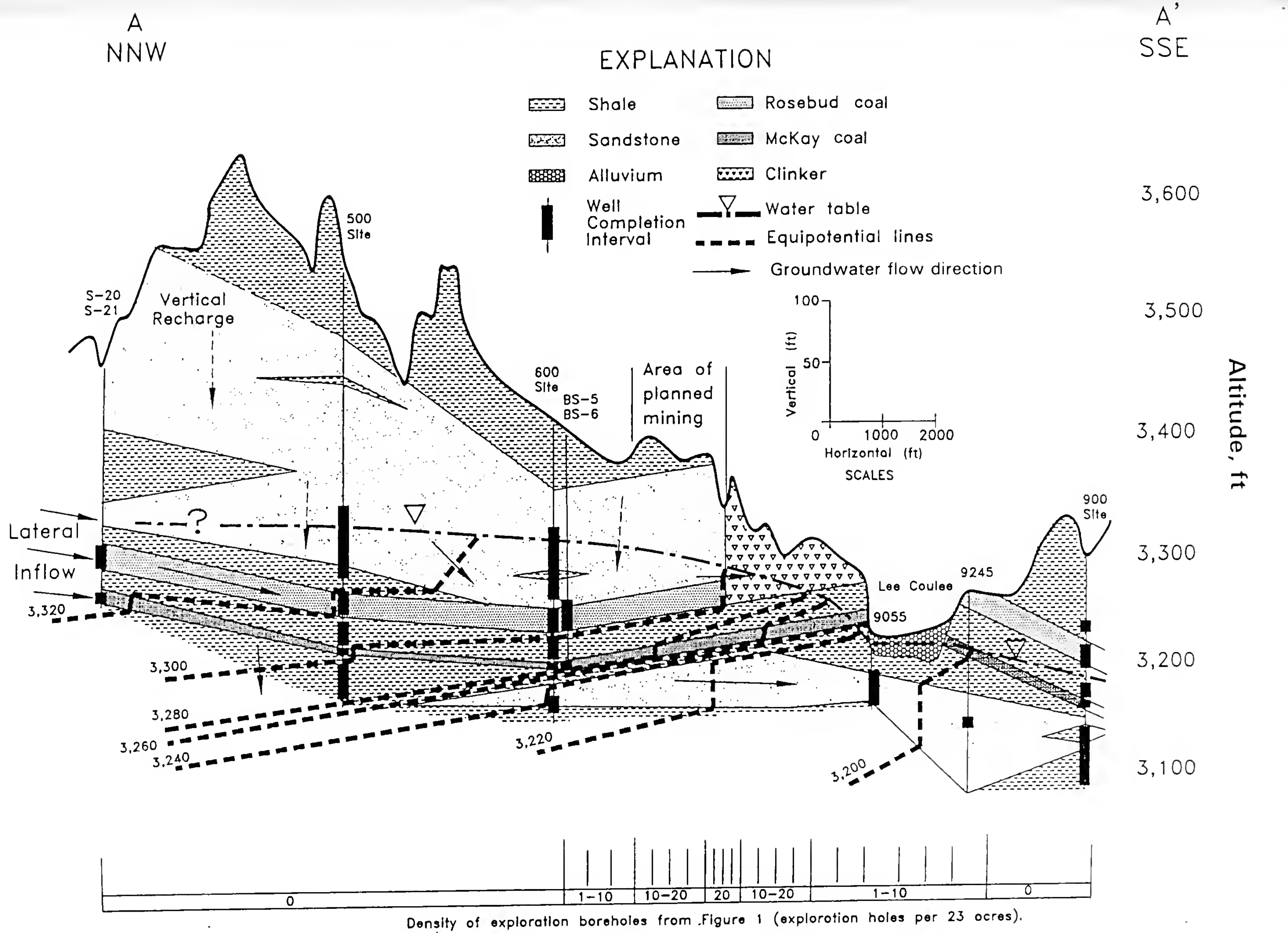

Figure 2. Geologic cross section showing potentiometric relationships based on earliest data available (1984). Data are from Montana Bureau of Mines and Geology (file data), and the mine company (on file at MT DEQ). Location of cross section is shown in Figure 1.

Groundwater quality reflects the concentrations of chemical constituents in the water and is explained in numerous publications, including Van Voast and Reiten (1988). Calculated dissolved solids concentration (CDS) is a measure of the quality of the water with higher CDS, indicating lower quality. CDS typically increases along a flow path as salts are dissolved from host rocks. On Figure 2, the best quality water (low CDS) should be toward the upper left, while lower quality (high CDS) should occur toward the lower right.

Based on MBMG data and company annual hydrology reports, the average CDS concentrations for the shallow aquifers in the study area are listed below in Table 1. The samples were collected between 1990 and 1994.

Table 1. Average CDS Concentrations for the Shallow Aquifers

Aquifer	Number of Samples	Minimum CDS (mg/L)	Maximum CDS (mg/L)	Average CDS (mg/L)
Overburden	30	530	4,420	2,330
Rosebud coal	33	1,100	4,430	2,520
Interburden	26	2,370	3,950	3,060
McKay coal	31	2,370	3,700	2,660
Underburden	85	2,140	3,610	2,150

Dissolved solids concentrations listed in Table 1 reflect the position of the sample point in the flow system and the mineralogy of the aquifer. The mineral content of the groundwater generally increases with depth, except for average concentrations from the interburden and underburden. The interburden is predominantly a shale unit with very low yield. High dissolved solids concentrations in interburden samples are a result of long-contact time between water and the geologic material, and salt availability. The apparently anomalous underburden water quality is discussed in section IV, part C.

IV. IMPACTS TO AQUIFERS ABOVE THE BASE OF THE MINE FLOOR

Impacts to groundwater resources caused by strip mining include water-level drawdown and increased dissolved solids load in groundwater (Van Voast and Reiten, 1988), (Van Voast, and others, 1977). Water-level declines are documented at all coal mine areas, and extend a few thousand feet in some areas and several miles in others. Near the study area, water-level declines in the Rosebud coal bed are about 14 ft at one monitor well (Figure 3a). Prior to opening of the nearby mine pit, a subtle decline in water level at this site was documented. Between 1984 (pre-mine) and 1994 (most recent data), drawdown in the Rosebud coal occurred over a large area adjacent to active mining (Figure 4).

After mining, a spoils aquifer developed in place of the mined aquifers. The spoils aquifer has not re-established in the study area; however, water-quality changes in other mined areas indicate the spoils aquifer will have a CDS load of about twice the pre-mine level, dominated by ions of calcium, magnesium, and sulfate.

V. IMPACTS TO UNMINED AQUIFERS

Not only are water levels being impacted in overburden and coal aquifers but also in aquifers underlying the mine floor. As with the Rosebud coal, water-level declines in the McKay coal were originally slight, but accelerated with the opening of the nearby mine pit (Figure 3b). Water-level declines were actually greater in the McKay than the Rosebud seam at the well cluster represented by Figures 3a and 3b. For the McKay coal, a map depicting change in water level during this period shows significant drawdown and an area of rising water level (Figure 5). In the underburden below the McKay coal, a large area of rising water level is indicated (Figure 6).

Drawdown and recharge have been documented in unmined aquifers. Some amount of drawdown can be explained by the reduction in vertical recharge caused by diverting water from the mine pit. However, the McKay coal is separated from the Rosebud by shales, which act as aquitards. Natural vertical recharge through these aquitards is probably small. Even with this poor natural communication, drawdowns in unmined aquifers have exceeded drawdowns in mined aquifers (Figure 3). Similar trends have been noted in other areas, such as the Canyon Coal near Decker, Montana (unpublished MBMG data).

The observed impacts to unmined aquifers are not predictable based on our understanding of the hydrologic system; therefore, an alternate explanation was sought. It was proposed (Van Voast and Reiten, 1988) that exploration drill holes could cause hydrologic communication between the mine and the stratigraphically deeper aquifers.

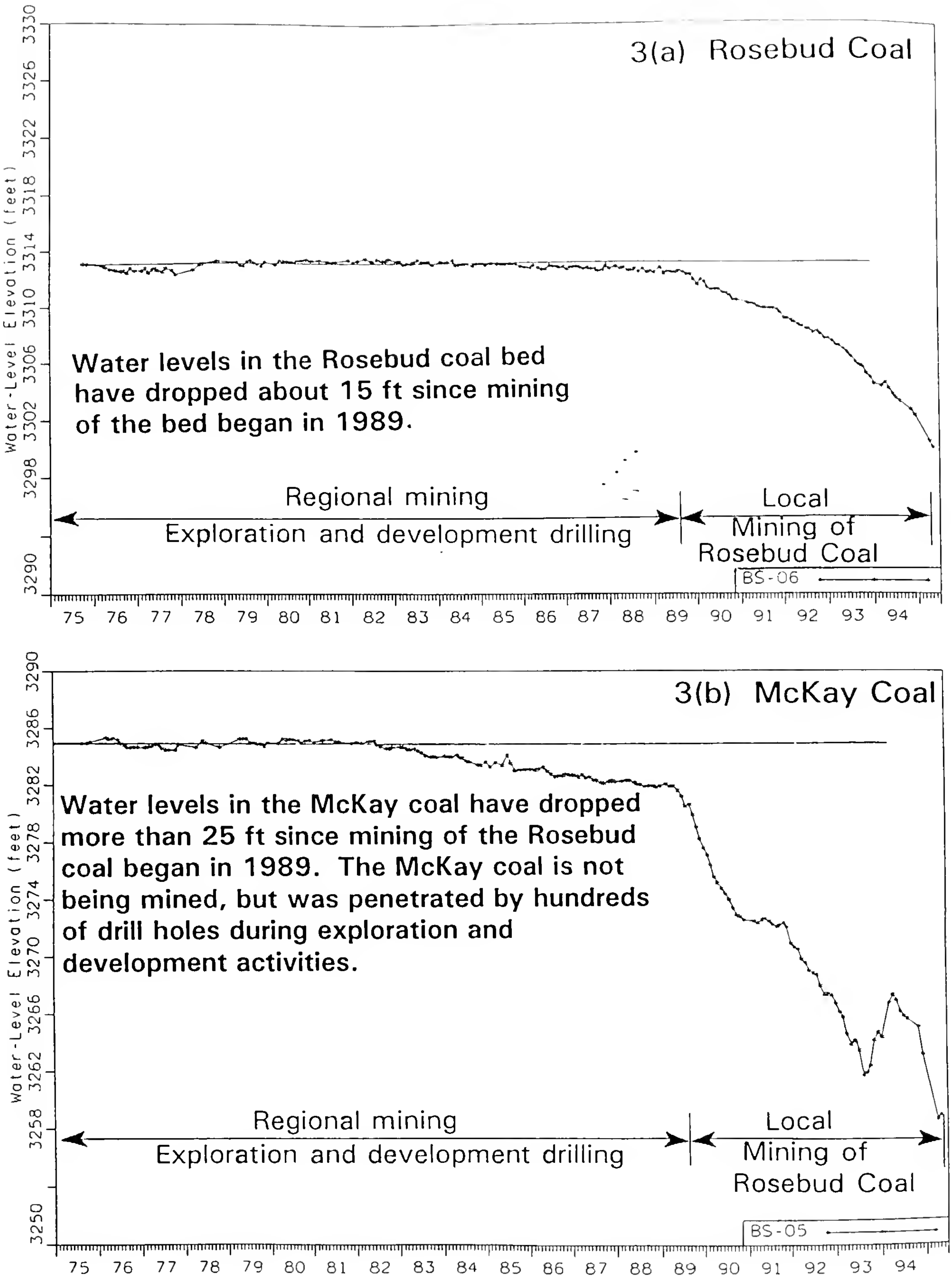

Figure 3. Examples of water-level hydrographs for Rosebud coal, 3(a); and McKay coal, 3(b) in study area. These wells are adjacent to each other and are about 1/8 mile north of the mine.

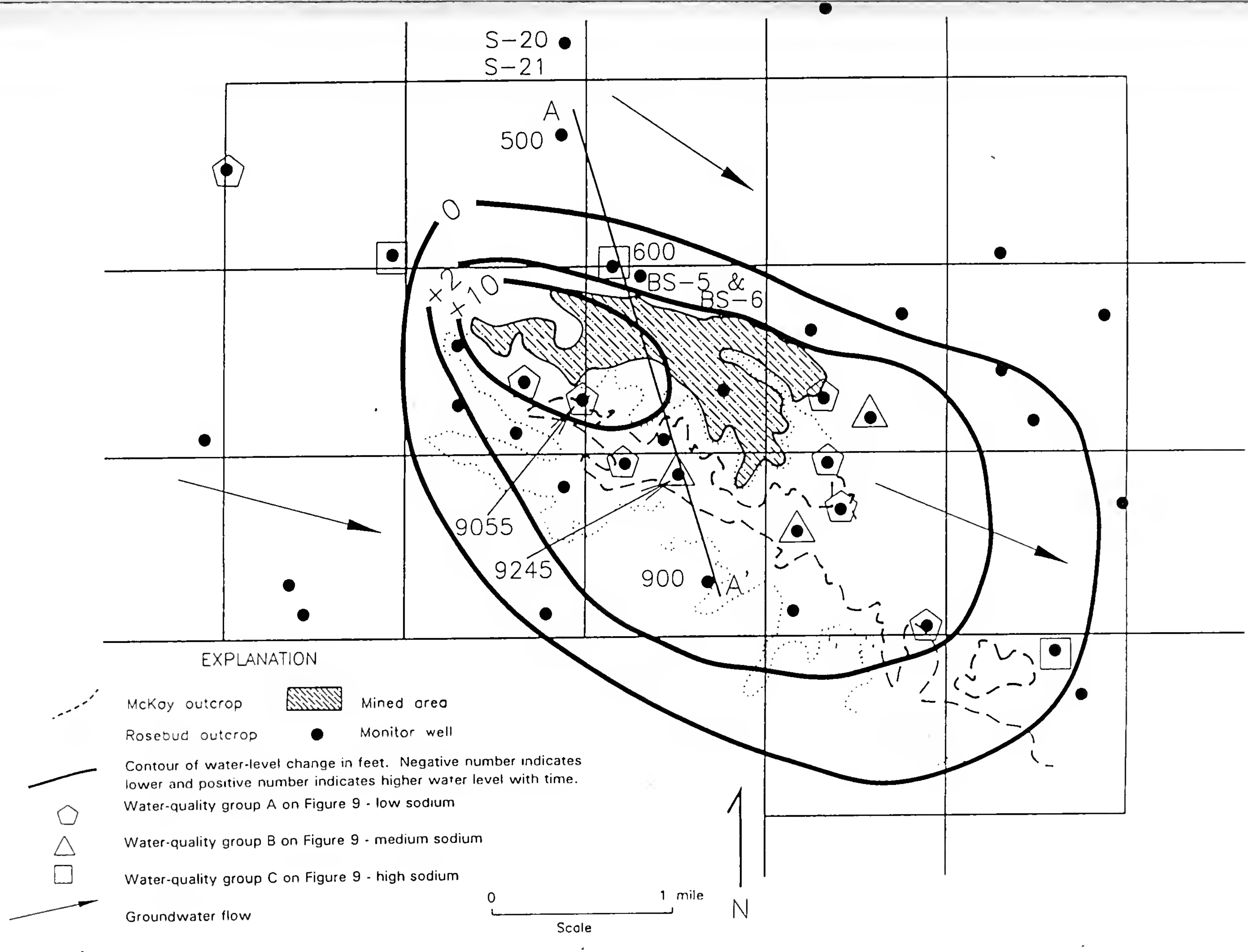

Figure 4. Map of change in the potentiometric surface of the Rosebud coal between 1984 and 1994.

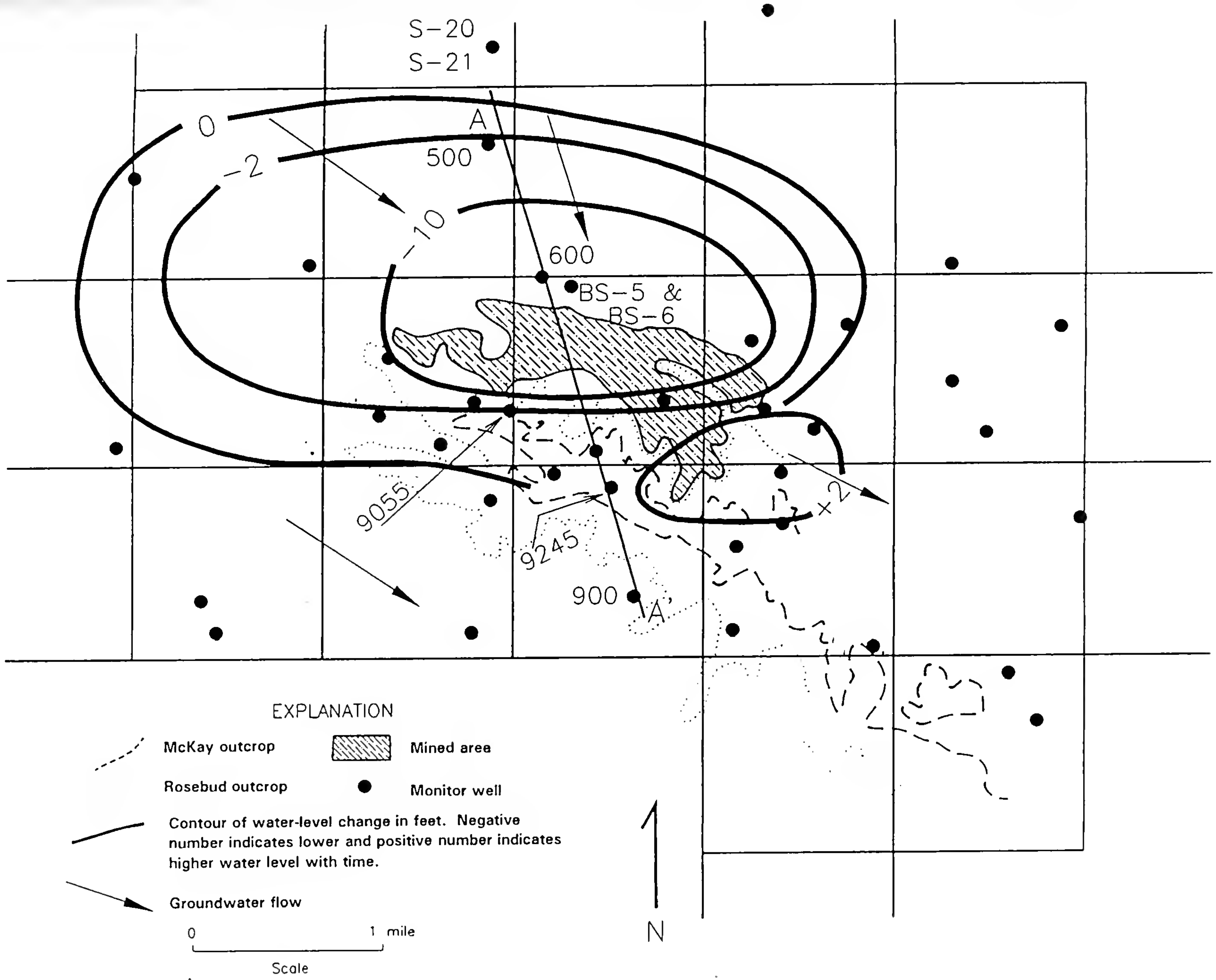

Figure 5. Map of change in the potentiometric surface of the McKay coal between 1984 and 1994.

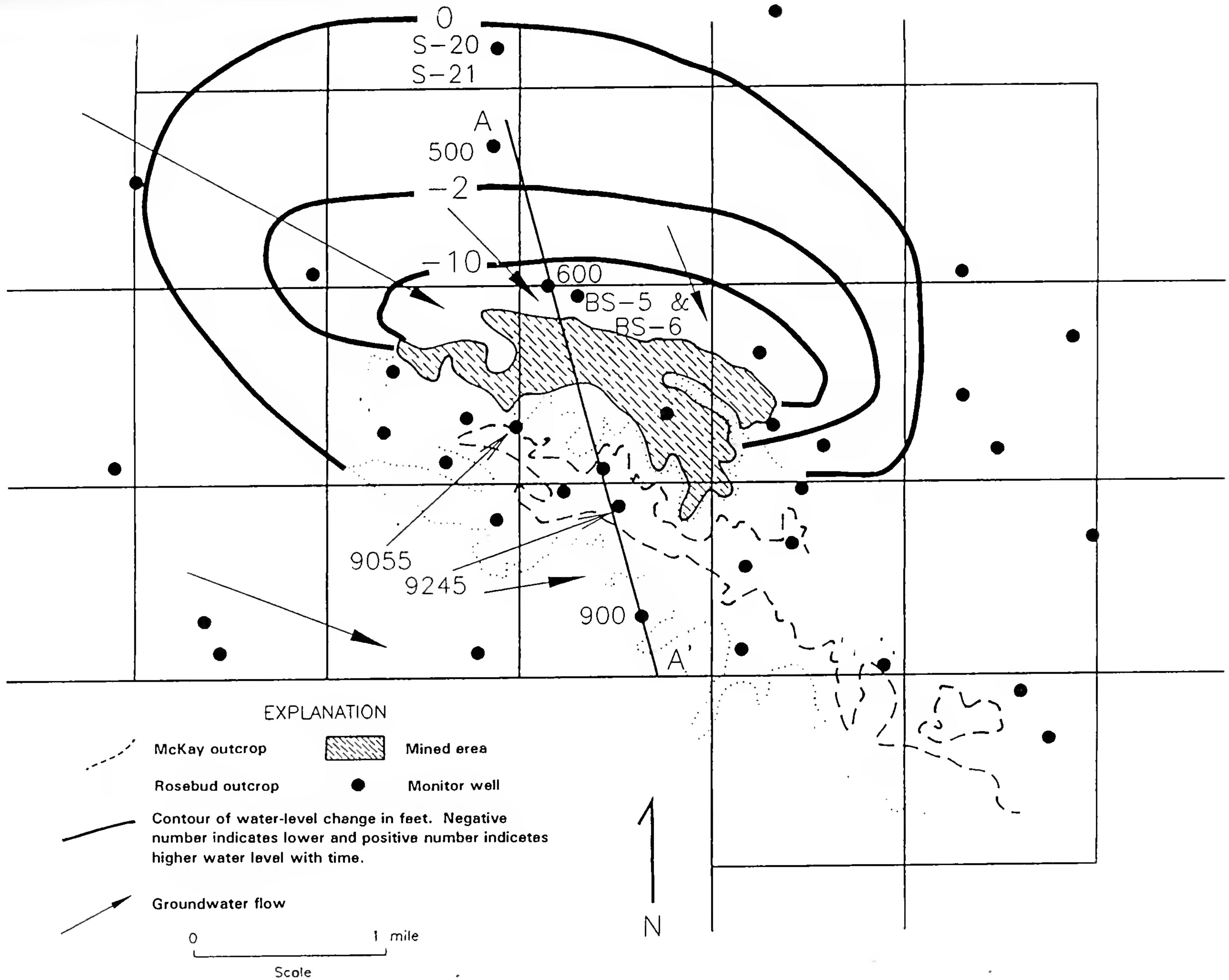

Figure 6. Map of change in the potentiometric surface of the underburden unit within about 50 ft of the McKay coal between 1984 and 1994 including locations of water-quality sample sites for underburden groups shown on the trilinear diagram.

In cross section, Figure 2 depicts the earliest available data for the study area, and Figure 7 shows data after seven years of mining. Distinct differences are seen in the positions of equipotential lines, indicating changes in hydrostatic pressure in the aquifers. In particular, pressure within the McKay coal is reduced in the area of exploration drilling to produce as much as 10 ft of change in potentiometric surface. In the same area, pressure within the underburden unit has increased by as much as 6 ft.

In pre-mining conditions, hydrostatic pressures exceeded the altitude of the Rosebud coal base, in all aquifers except the SubMcKay unit, in the area of planned mining (Figure 2). After the Rosebud coal was removed by mining, hydrostatic pressures were reduced to approximately the base of the Rosebud coal. Hydrostatic pressures in the SubMcKay unit were below the base of the Rosebud coal before and after mining.

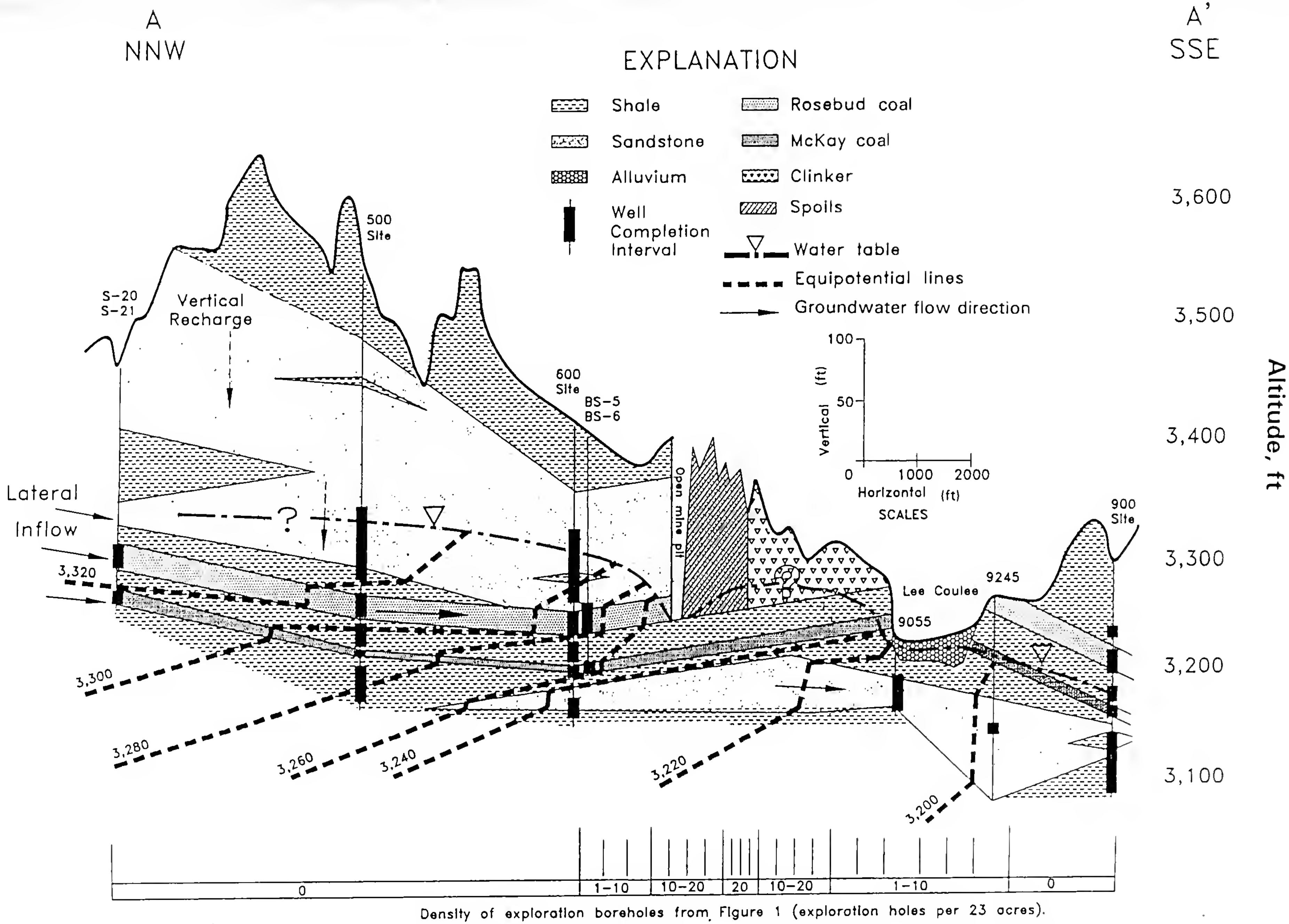

Figure 7. Geologic cross section showing potentiometric relationships based on most recent data available, which is after the mine area opened (1994). Data are from Montana Bureau of Mines and Geology (file data), and the mine company (on file at MT DEQ). Location of cross section is shown on Figure 1.

VI. MEASURING WATER-LEVEL IMPACTS IN UNMINED AQUIFERS

Two conceptual models were developed to describe and quantify water-level impacts to the unmined aquifers at this site. With refinement, these methods may apply to other areas. The methods focus on A) spatial water-quality relationships in the underburden aquifer below the McKay coal, and B) flow through a hypothetical single borehole based on mass balance.

A third technique was considered but deemed inappropriate for the transient conditions that exist during mining and pit dewatering. This technique involves assessing the refraction angle of groundwater flow lines at lithologic boundaries, which relates to the ratio of hydraulic conductivities on either side of the boundary (Free and Cherry, 1979, pg 172). After reclamation is completed, this technique may be used to compare pre-mining and post-mining flow directions.

A. Groundwater Quality

Given the earlier discussion of water-quality evolution, if water from shallower aquifers is infiltrating to the underburden unit, then a plume of lower CDS water should be evident in the deeper unit. Table 1 lists average CDS concentrations for each aquifer and shows increasing values with increasing depth, except for the underburden. Lower average CDS concentrations may indicate infiltration of shallow water to the underburden. Water sample data from company and MBMG files for underburden wells in the study area are plotted in Trilinear form on Figure 8. The trilinear shows three groups of water quality (labeled A, B, and C), indicating generally increasing maturity along the flow path from the top of the trilinear (A) to the bottom of the trilinear (C). This change in position is due entirely to the change in cation concentrations.

These data do not define a clear trend when plotted on a mine map (Figure 6). However, some of group A do plot downgradient of groups B and C, and downgradient of dense drill-hole patterns. This indicates that fresher water, possibly from shallower bedrock aquifers, is infiltrating through boreholes into the underburden unit.

B. Mass Balance for a Single Borehole

Water levels declined in the overburden, Rosebud coal, interburden, and McKay coal, from 1984 (first data) to 1989 (last data before mining impacts) to indicate water loss. In the underburden unit below the McKay, water levels rose, indicating a water gain. Flow rate from the losing aquifers should approximate the gain in the underburden unit if the trends are related.

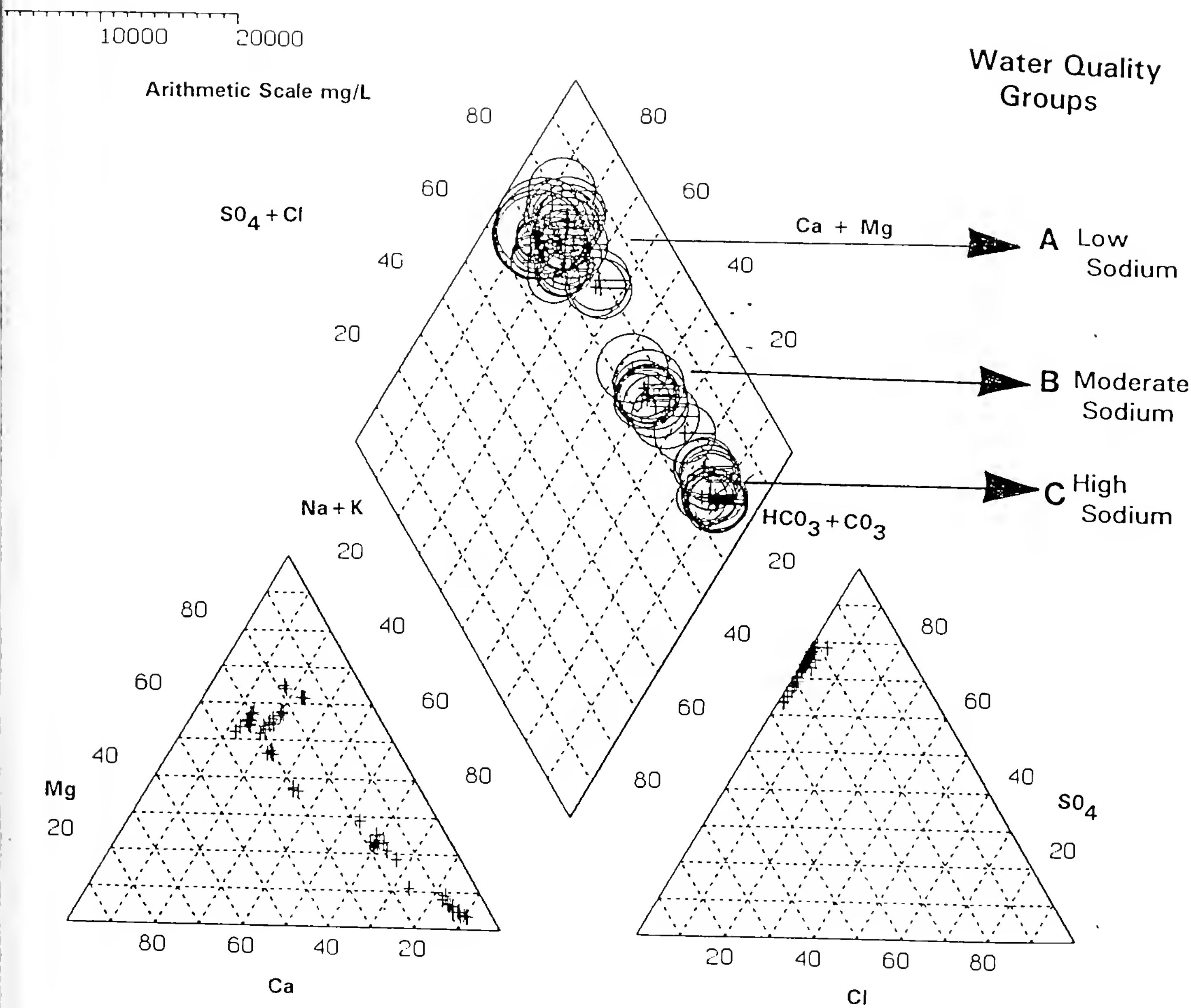

Figure 8. Trilinear diagram of underburden water samples.

Flow rate between aquifers can be estimated from available hydrogeologic data. Data on coal-mine area aquifers are contained in MBMG reports and publications, and in company reports on file at Department of Environmental Quality. The following calculations draw on data from both sources.

After the mine pit opens, nearby water-level changes are dominated by horizontal flow to the pit and vertical flow through the boreholes. To avoid the effects of mine dewatering, the following calculations of vertical flow are based on data collected before the opening of the nearby pit. Values used are listed in Table 2. Water-level values represent a hypothetical drill hole located, about 1,000 feet south-southeast of well site 600 on the cross section shown on Figure 2. Values for change in head listed in Table 2 were interpreted from Figure 2 (1984 data) and from potentiometric surfaces for 1989 data (MBMG file data). The data are estimated to be accurate to about one foot. Flow was calculated for a 6-in.-diameter borehole during 1984-1989.

Table 2. Calculated Rates of Groundwater flow through an Incompletely Plugged Borehole

Aquifer	1984 Water Level (ft)	1989 Water Level (ft)	∇h Change in Head (ft)	Transmissivity (ft^2/day)	Storativity
Overburden	3308	3307	-1	50	.1
Rosebud Coal	3305	3304	-1	6	1E-5
McKay Coal	3280	3270	-10	6	1E-5
Underburden	3223	3228	+5	60	1E-5

The following equations show the Jacob solution to the Theis equation using consistent units, and the calculation sequence used in this mass balance.

Jacobs equation:

$$Q=[\nabla h * 4 * \Pi * T] / [2.3 * \log \{(2.25 * T * t) / (S * r^2)\}$$

Explanation of symbols:

Q = groundwater flow (ft^3/day)
∇h = head change 1984-1989 (ft)
T = aquifer transmissivity (ft^2/day)
t = time (day)
S = storativity
r = borehole radius (0.25ft)

Using the Jacob equation, flow rates were calculated for a single borehole, and as shown in Table 3 the calculated gains match reasonably well with the calculated losses. The number of boreholes that are actually contributing to the flow cannot be estimated; therefore, the calculations were limited to a single hypothetical borehole.

Table 3. Calculated Aquifer Flow Rates for a Single Borehole

Aquifer	Flow Rate (ft^3/day)	Flow Rate (gpm)	
Overburden	-36	-0.2	
Rosebud Coal	-3	-0.02	total losing flow
McKay Coal	-31	-0.2	rate: -0.4 gpm
Underburden	141	0.7	total gaining flow flow rate: 0.7 gpm

The calculated losing flow rate is 70 ft^3/day (0.4 gpm), and the calculated gaining flow rate is 140 ft^3/day (0.7 gpm). These calculations probably result in overly large flow rates because interference effects from nearby wells were not included in the equations. The effects of partially plugged boreholes also are not included in this calculation but should not change the results because the calculations are based on pressure change in the aquifers ,not hydraulic conductivity of the boreholes.

After mining is complete and the spoils aquifer is established, groundwater carrying a high dissolved solids load will be able to move vertically to deeper aquifers. The annual salt load that could be added to the underburden by spoils discharge through open holes was estimated based on average CDS concentrations (Table 1) and flow rate calculations for a single hypothetical borehole (Table 2). The spoils recharge water was assumed to be a mixture of overburden and Rosebud coal water at a ratio that is proportionate to the transmissivity values of the aquifers (50 and 6 ft^2/day, respectively). Based on this ratio, the recharge water to the spoils was estimated to be 90% overburden water and 10% Rosebud coal water, with a combined CDS concentration of about 2,350 mg/L. The spoils water CDS concentration was estimated to be 4,700 mg/L based on an increase of 200% over the combined overburden/Rosebud coal water. From Table 2, the combined flow rate from these two aquifers to the underburden aquifer is 40^3/day. Therefore the CDS load increase in the underburden over pre-drilling conditions was estimated to be about 30 tons per year through a single open borehole with a flow increase of about $14,600^3$/year (40 ft^3/day). Again, this is a hypothetical borehole and does not consider interference between boreholes, which would decrease the flow calculation from these data.

VII. CONCLUSIONS

Drawdowns, due to mining and related pit dewatering, will recover, probably within about three years after the closing of the mine pit (Van Voast and Reiten, 1988). Observed drawdown in deeper unmined aquifers does not fit existing models, because drawdown in unmined aquifers exceeds that in mined aquifers. Exploration drill holes are channels of higher hydraulic conductivity (relative to surrounding rock units) and allow vertical migration of groundwater. The magnitude of drawdown in unmined aquifers is due to aquifer properties plus reduced recharge from shallower aquifers and loss to boreholes.

Recovery of the water levels will occur. Spoils aquifer water level (pressure) will stabilize, at a level that is potentially 30 ft higher than present impacted levels. At that time the downward gradient will be 30 ft higher than it is now. The higher gradient will permit more movement of water into the deeper aquifer. In the post-mine setting, water moving through the boreholes will include spoils water carrying a high dissolved solids load. The water-level impacts that are now being documented may be early warnings of water-quality impacts to come.

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